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(54) **METHOD AND APPARATUS TO CONTROL A CONTINUOUSLY VARIABLE TRANSMISSION**

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F16H 61/662	(2006.01)
F16H 9/04	(2006.01)
F16H 59/38	(2006.01)
F16H 59/14	(2006.01)
F16H 63/24	(2006.01)

(52) **U.S. Cl.**

CPC ***F16H 61/66272*** (2013.01); ***F16H 9/04*** (2013.01); ***F16H 59/14*** (2013.01); ***F16H 59/38*** (2013.01); ***F16H 63/24*** (2013.01); *F16H 2059/148* (2013.01); *F16H 2710/04* (2013.01); *F16H 2710/24* (2013.01)

(58) **Field of Classification Search**

None

See application file for complete search history.

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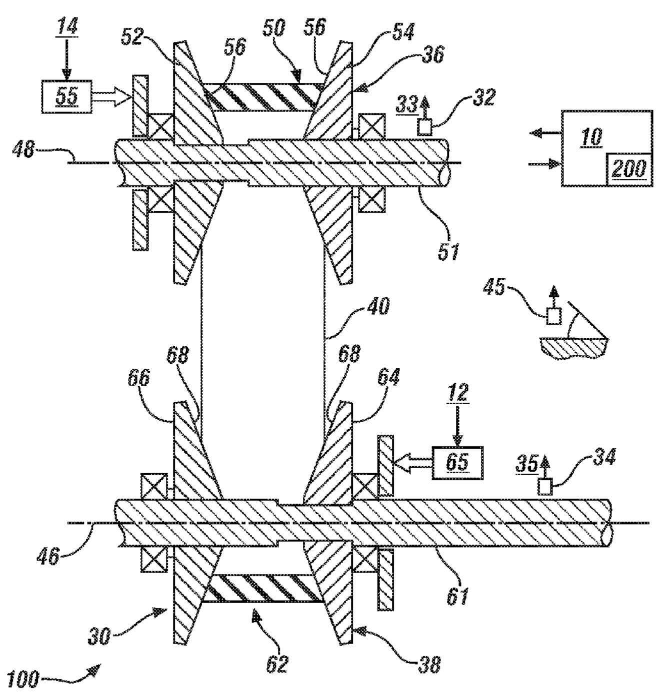
(57) **ABSTRACT**

A method for controlling a variator of a continuously variable transmission includes combining, by a controller, a periodically repeating excitation signal and a desired variator speed ratio signal. A variator ratio derivative is determined based upon the desired variator speed ratio signal combined with the excitation signal. A variator control parameter is determined based upon the variator ratio derivative. The variator control parameter is sent to the controller for controlling the variator in response thereto.

16 Claims, 1 Drawing Sheet



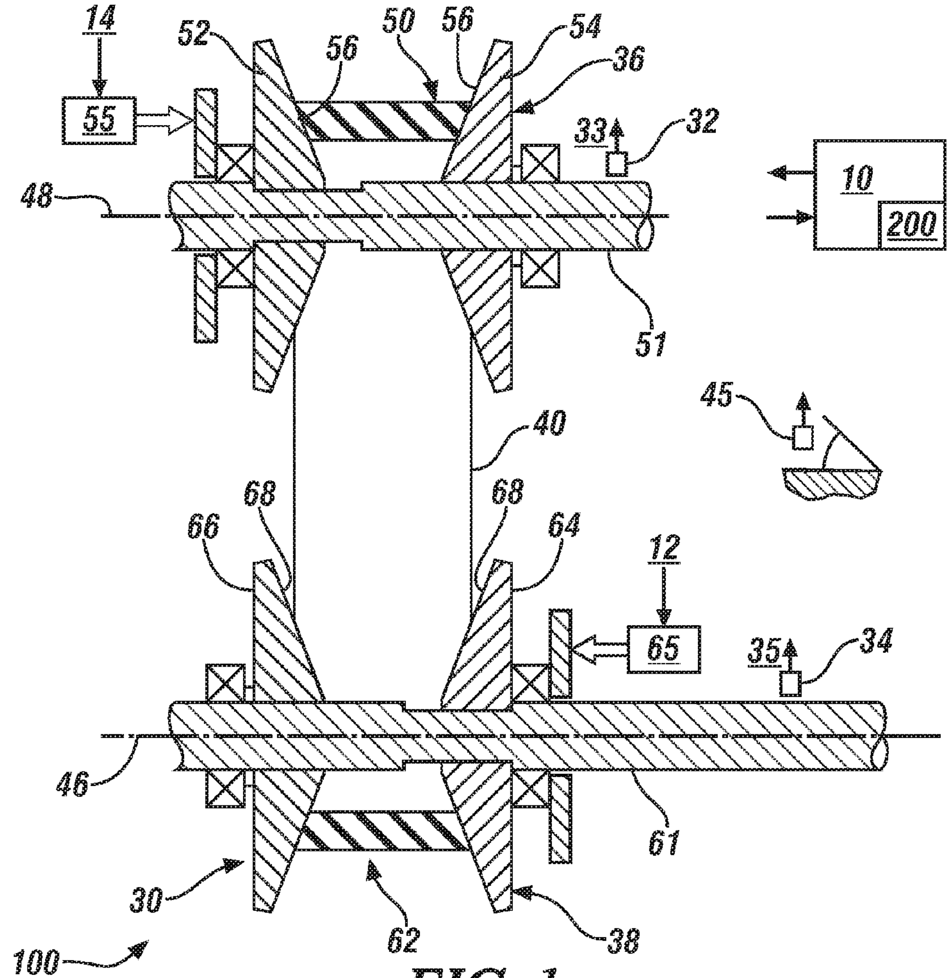

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FIG. 1

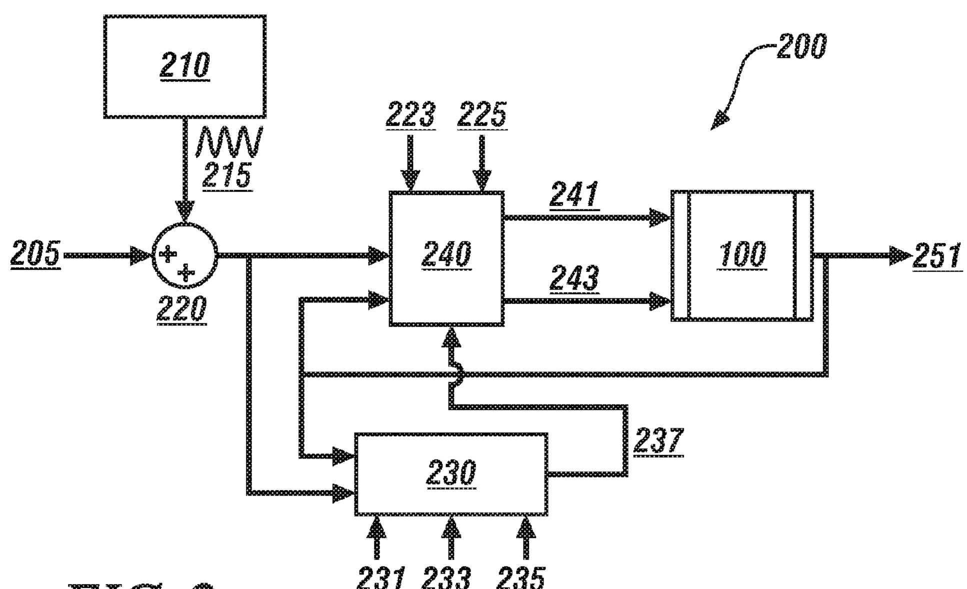
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FIG. 2

METHOD AND APPARATUS TO CONTROL A CONTINUOUSLY VARIABLE TRANSMISSION

TECHNICAL FIELD

This disclosure relates to a continuously variable transmission for a vehicle powertrain, and a method and control routine associated therewith.

BACKGROUND

Powertrains having an internal combustion engine coupled to a continuously or infinitely variable transmission (CVT) may be employed to provide tractive effort in vehicles. A CVT is capable of continuously changing an input/output speed ratio over a range between a minimum (underdrive) ratio and a maximum (overdrive) ratio, thus permitting infinitely variable selection of engine operation that achieves a preferred balance of fuel consumption and engine performance in response to an operator torque request.

Known belt-type continuously variable transmissions include two pulleys, each having two sheaves. A belt runs between the two pulleys, with the two sheaves of each of the pulleys sandwiching the belt therebetween. Frictional engagement between the sheaves of each pulley and the belt couples the belt to each of the pulleys to transfer torque from one pulley to the other. One of the pulleys may function as a drive, primary or input pulley so that the other pulley, i.e., a driven, secondary or output pulley can be driven. The gear ratio is the ratio of the torque of the driven pulley to the torque of the drive pulley. The gear ratio may be changed by moving the two sheaves of one of the pulleys closer together and the two sheaves of the other pulley farther apart, causing the belt to ride higher or lower on the respective pulley.

Known toroidal continuously variable transmissions include discs and roller mechanisms that transmit power between the discs. The toroidal continuously variable transmission includes at least one input disc, connected to the engine, and one output disc operatively connected to the transmission output. The input disc and output disc define a cavity therebetween. The cavity defines a toroidal surface. The roller mechanism is placed within the cavity and is configured to vary the torque transmission ratio as the roller mechanism moves across the toroidal surface.

SUMMARY

A method for controlling a variator of a continuously variable transmission includes combining, by a controller, a periodically repeating excitation signal and a desired variator speed ratio signal. A variator ratio derivative is determined based upon the desired variator speed ratio signal combined with the excitation signal. A variator control parameter is determined based upon the variator ratio derivative. The variator control parameter is sent to the controller for controlling the variator in response thereto.

The above features and advantages, and other features and advantages, of the present teachings are readily apparent from the following detailed description of some of the best modes and other embodiments for carrying out the present teachings, as defined in the appended claims, when taken in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

One or more embodiments will now be described, by way of example, with reference to the accompanying drawings, in which:

FIG. **1** schematically illustrates elements of a variator of a belt-type continuously variable transmission (CVT) having an improved control routine, in accordance with the disclosure; and

FIG. **2** schematically shows a block diagram of a CVT control routine that includes introducing a repeating signal to a variator reference speed ratio to control a CVT system, in accordance with the disclosure.

DETAILED DESCRIPTION

Referring now to the drawings, wherein the depictions are for the purpose of illustrating certain exemplary embodiments only and not for the purpose of limiting the same, FIG. **1** schematically illustrates elements of a variator **30** of a belt-type continuously variable transmission (CVT) **100** that is advantageously controlled by a controller **10** that is capable of executing a control routine **200** described with reference to FIG. **2**. The variator **30** transfers torque between a first rotating member **51** and a second rotating member **61**, with the first and second rotating members **51**, **61** each rotatably coupled to any one of a primary power source including either an internal combustion engine or an electric motor/generator, and an output member in the form of a planetary gear set of a transmission or an output member coupled to a driveline for delivering tractive torque to vehicle drive wheels. The first rotating member **51** is nominally referred to herein as an input member, and the second rotating member **61** is nominally referred to herein as an output member.

The variator **30** includes a first, or primary pulley **36**, a second, or secondary pulley **38** and flexible continuous rotatable device **40** that rotatably couples the first and second pulleys **36**, **38** to transfer torque therebetween. The first pulley **36** rotatably attaches to the input member **51** and the second pulley **38** rotatably attaches to the output member **61**, and the rotatable device **40** is adapted to transfer torque between the first and second pulleys **36**, **38** and thus between the input and output members **51**, **61**. The first pulley **36** and input member **51** rotate about a first axis **48**, and the second pulley **38** and output member **61** rotate about a second axis **46**. The continuous rotatable device **40** can be a belt, a chain, or another suitable flexible continuous device.

The first pulley **36** is split perpendicular to the first axis **48** to define an annular first groove **50** that is formed between a moveable sheave **52** and a stationary sheave **54**. The moveable sheave **52** axially moves or translates along the first axis **48** relative to the stationary sheave **54**. For example, the moveable first sheave **52** may be attached to the input member **51** via a splined connection, thereby allowing axial movement of the moveable first sheave **52** along the first axis **48**. The stationary first sheave **54** is disposed opposite the moveable first sheave **52**. The stationary first sheave **54** is axially fixed to the input member **51** along the first axis **48**. As such, the stationary first sheave **54** does not move in the axial direction of the first axis **48**. The moveable first sheave **52** and the stationary first sheave **54** each include a first groove surface **56**. The first groove surfaces **56** of the moveable first sheave **52** and the stationary first sheave **54** are disposed opposite each other to define the annular first groove **50** therebetween. The opposed first grooved surfaces **56** preferably form an inverted frustroconical shape such that a movement of the moveable first sheave **52** towards the stationary first sheave **54** increases an outer pulley diameter of the annular first groove **50**. An actuator **55** is arranged with the first pulley **36** to control an axial position of the moveable first sheave **52** in response to a first signal **14**, including urging the moveable first sheave **52** towards the stationary first sheave **54**. In one embodiment, the actuator **55** is a hydraulically-controlled device and the first signal **14** is a hydraulic pressure signal.

The second pulley **38** is split perpendicular to the second axis **46** to define an annular second groove **62** therebetween. The annular second groove **62** is disposed perpendicular to the second axis **46**. The second pulley **38** includes a moveable sheave **64** and a stationary sheave **66**. The moveable sheave **64** axially moves or translates along the second axis **46** relative to the stationary sheave **66**. For example, the moveable second sheave **64** may be attached to the output member **61** via a splined connection, thereby allowing axial movement of the moveable second sheave **64** along the second axis **46**. The stationary second sheave **66** is disposed opposite the moveable second sheave **64**. The stationary second sheave **66** is axially fixed to the output member **61** along the second axis **46**. As such, the stationary second sheave **66** does not move in the axial direction of the second axis **46**. The moveable second sheave **64** and the stationary second sheave **66** each include a second groove surface **68**. The second groove surfaces **68** of the moveable second sheave **64** and the stationary second sheave **66** are disposed opposite each other to define the annular second groove **62** therebetween. The opposed second grooved surfaces **68** preferably form an inverted frustroconical shape such that a movement of the moveable second sheave **64** towards the stationary second sheave **66** increases an outer pulley diameter of the annular second groove **62**. An actuator **65** is arranged with the second pulley **38** to control an axial position of the moveable second sheave **64** in response to a second signal **12**, including urging the moveable second sheave **64** towards the stationary second sheave **66**. In one embodiment, the actuator **65** is a hydraulically-controlled device and the second signal **12** is a hydraulic pressure signal. A ratio of the outer pulley diameter of the first pulley **36** and the outer pulley diameter of the second pulley **38** defines a transmission torque ratio. Other elements, such as clutch assemblies in the form of selectable one-way clutches and the like may be deployed between the variator **30** and other powertrain and driveline components and systems.

The controller **10** for monitor sensor inputs and controlling operation of powertrain elements including the CVT **100** may be positioned external thereto. Driver input devices such as an accelerator pedal and associated accelerator pedal position sensor **45** can be monitored to determine an operator torque request. Various sensors are suitably positioned for sensing and providing signals. An input speed sensor **32** may be mounted near the input member **51** to generate an input speed signal **33**. A variator output speed sensor **34** may be mounted near the output member **61** to generate an output speed signal **35**. The variator input speed sensor **32** and variator output speed sensor **34** may be any suitable rotation position/speed sensing device, such as a Hall-effect sensor. The input speed signal **33** and the output speed signal **35** may be combined in the controller **10** to provide an actual variator speed ratio. Although the signals from the sensors are shown as discrete lines, they may be included on a common bus, sent wirelessly or via multiple conductor cables or the like for use in the present disclosure.

The controller **10** may include digital processing capability that includes executable control routines that determine control signals for actuators based on input signals such as vehicle speed and engine torque. The controller **10** and similar terms control module, module, control, control unit, processor and similar terms refer to any one or various combinations of Application Specific Integrated Circuit(s) (ASIC), electronic circuit(s), central processing unit(s), e.g., microprocessor(s) and associated memory and storage devices (read only, programmable read only, random access, hard drive, etc.) executing one or more software or firmware programs or routines, combinational logic circuit(s), input/output circuit(s) and devices, signal conditioning and buffer circuitry and other components to provide a described functionality. Software, firmware, programs, instructions, control routines, code, algorithms and similar terms mean any controller-executable instruction sets including calibrations and look-up tables. Each controller executes control routine (s) to provide desired functions, including monitoring inputs from sensing devices and other networked controllers and executing control and diagnostic routines to control operation of actuators. Routines may be executed at regular intervals, for example each 100 microseconds. Communications between controllers and between controllers, actuators and/or sensors may be accomplished using a direct wired link, a networked communications bus link, a wireless link or any another suitable communications link. The CVT control routine **200** is implemented as one or a plurality of elements of the controller **10** shown with reference to FIG. **1**, with a detailed description provided in FIG. **2**.

FIG. **2** schematically shows a block diagram of a CVT control routine **200** that can be employed in controlling a CVT system, e.g., an embodiment of the CVT **100** shown with reference to FIG. **1**. Overall, the CVT control routine **200** includes introducing a periodically repeating signal to the variator reference speed ratio and decomposing the result into an analytical expression. The periodically repeating signal introduced to the variator reference speed ratio is sinusoidal in one embodiment and as described herein, but may take any suitable form to determine a ratio change coefficient k for controlling operation of the CVT **100** employing the CVT control routine **200** described herein.

The CVT control routine **200** analytically computes a variator ratio derivative $\dot{r}$ which is employed with a shift force Fshift to calculate the ratio change coefficient k for controlling operation of the CVT **100** in response to an operator torque request. The sinusoidal excitation to the speed or torque ratio of the variator of the CVT **100** is introduced to calculate the ratio of ratio change rate and the balance of primary/secondary pulley forces for different conditions, allowing the variator ratio derivative to be determined without relying on noisy differentiation from digital signal filters and/or estimators. This is accomplished by advantageously calculating the variator ratio derivative of the periodically repeating excitation signal employing the frequency composition of the measured ratio. In one embodiment the frequency composition of the measured ratio is obtained using a discrete Fourier transform (FFT). Alternatively, a plurality of sinusoids at difference frequencies and phases is used. This calculation is then divided by the shift force Fshift as a function of the measured or calculated primary and secondary forces at the pulleys of the variator. The division yields a torque or speed ratio rate coefficient that is characterized for different operation conditions of the variator that include, but are not limited to speed ratio, input/output speed, primary/secondary forces, torque ratio coefficient, temperature, friction coefficient between belt/chain and pulleys, life or purity of the transmission fluid, among other conditions.

The CVT control routine **200** includes a signal generator **210**, a ratio change coefficient generator **230** and a controller **240** to determine a primary pressure command **241** and a secondary pressure command **243**, both which are employed to control operation of the CVT **100** in response to a desired variator speed ratio (VSR) **205**.

A CVT control parameter in the form of the desired VSR **205** is determined based upon monitored and estimated operating conditions related to vehicle speed and engine torque.

The desired VSR **205** is a ratio between transmission input speed and transmission output speed that is employed in controlling pressures of one or both the primary pulley **36** and the secondary pulley **38** of the CVT **100**. Controlling pressures of one or both the primary pulley **36** and the secondary pulley **38** of the CVT **100** described with reference to FIG. **1** can be achieved by controlling first and second signals **14**, **12** to apply requisite pressures to the first and second actuators **55**, **65** to effect the desired VSR **205**, wherein the requisite pressures are preferably in the form of the primary pressure command **241** and the secondary pressure command **243**.

The sinusoidal signal generator **210** generates a sinusoidal VSR signal **215** that is added to the desired VSR **205** employing adder **220** to generate a combined VSR signal **221**, wherein the sinusoidal VSR signal **215** has a magnitude that is +/−about 5% of a maximum value for the desired VSR **205** at a known frequency f_1 in one embodiment. The combined VSR signal **221** and a presently measured actual variator speed ratio **251** are provided as inputs to the ratio change coefficient generator **230** and the controller **240**.

The ratio change coefficient generator **230** employs one of the combined VSR signal **221** or the presently measured actual variator speed ratio **251** to periodically determine and update a value for a ratio change coefficient k **237** based upon monitored CVT operating signals including a primary pulley force or pressure F_{prim} **231**, a secondary pulley force or pressure F_{sec} **233** that corresponds to a commanded secondary shift force for controlling the variator and a ratio change coefficient kpks **235**, which represents a ratio of F_{prim} and F_{sec} that accounts for force from hydraulic pressure and force from centrifugal pressure and spring force. The ratio change coefficient kpks **235** is related to variator speed ratio and a variator torque capacity ratio, and is dependent upon input torque, input speed, output speed, transmission fluid temperature, transmission fluid quality and other factors.

One of the combined VSR signal **221** and the presently measured actual variator speed ratio **251** can be employed to develop an equation in the following form using fast Fourier transform (FFT) analysis.

$$r=a_1\cos(2\pi f_1 t+\phi_1)+a_2\cos(2\pi f_2 t+\phi_2)+\ldots \quad [1]$$

wherein:

r represents a selected one of either the combined VSR signal **221** or the presently measured actual variator speed ratio **251**;

$a_1, a_2, \ldots$ are coefficients associated with magnitudes of the related signals;

$f_1, f_2, \ldots$ are frequencies of the related signals, and

$\phi_1, \phi_2, \ldots$ are phase shifts associated with the related signals.

The calculated ratio of ratio change rate and a balance of primary and secondary pulley forces can be determined for different conditions by taking advantage of the fact that the excitation, e.g., the combined VSR signal **221** has a sinusoidal component. This includes determining a derivative of the combined VSR signal **221**, i.e., determining a variator ratio derivative $\dot{r}$. The frequency composition of the selected ratio is employed to calculate the variator ratio derivative $\dot{r}$, which takes the following form:

$$\dot{r}=k(F\text{shift}) \quad [2]$$

$$\dot{r}=k(F_{prim}-kpksF_{sec}) \quad [3]$$

$$k=\frac{\dot{r}}{(F_{prim}-kpksF_{sec})} \quad [4]$$

wherein:

F_{prim} is the primary pulley force or pressure **231**;

F_{sec} is the secondary pulley force or pressure **233**, which corresponds to a commanded secondary shift force for controlling the variator;

kpks is an empirical coefficient **235**, which represents a ratio of F_{prim} and F_{sec} that accounts for force from hydraulic pressure, force from centrifugal pressure and spring force; and

k is the ratio change coefficient.

The variator ratio derivative $\dot{r}$ can be determined as a derivative of Eq. 1, above, resulting in the following.

$$\dot{r}=a_1 2\pi f_1\sin(2\pi f_1 t+\phi_1)+a_2 2\pi f_2\cos(2\pi f_2 t+\phi_2)+\ldots \quad [5]$$

In one embodiment the frequency composition is obtained using a discrete Fourier transform (FFT). Alternatively, a bank of sinusoids at difference frequencies and phases and correlation is used to determine the frequency composition. This calculation is divided by the shift force as a function of the measured or calculated primary and secondary forces at the pulleys of the variator to determine the ratio change coefficient k **237**, which is provided as input to controller **240**.

Controller **240** determines the primary pressure command **241** and secondary pressure command **243**, both which are employed to control operation of the CVT **100** in response to the desired VSR command **205**, a commanded engine torque **223**, an operator torque request **225** and the presently measured actual variator speed ratio **251** that is determined based upon measured speeds from the from the variator of the CVT **100** including the input speed signal **33** and the output speed signal **35**. The operator torque request **225** is based upon information including driver information, such as the operator torque request via the accelerator pedal position sensor **45** as shown. Other inputs may include vehicle information such as the present vehicle speed.

Controller **240** determines the primary pressure command **241** and secondary pressure command **243** to control actuators of the CVT **100** based upon the variator ratio derivative $\dot{r}$ using the following relationship:

$$\dot{r}=k(VSR,\omega_p)*[F_{prim}-kpks(VSR,TCR)F_{sec}] \quad [6]$$

wherein:

k is the ratio change coefficient **237**;

kpks is the ratio change coefficient **235** related to variator speed ratio and a variator torque capacity ratio, and is dependent upon input torque, input speed, output speed, transmission fluid temperature, transmission fluid quality and other factors;

VSR is the desired VSR command **205**;

ω_p is the input speed; and

TCR is a torque capacity factor for the CVT.

The necessary adjustments needed to effect the primary pressure command **241** and the secondary pressure command **243** are employed to control the CVT **100**. This includes the controller **10** sending first and second signals **14**, **12** to drive the first and second actuators **55**, **65** based thereon to move the moveable sheave **52** of the first pulley **36** and the moveable sheave **64** of the second pulley **38** as described above. This movement causes a change that causes a change in torque transfer across the variator of the CVT **100**.

Alternatively, the presently measured actual variator speed ratio **251** can be employed by the ratio change coefficient generator **230** to periodically determine and update a value for the ratio change coefficient k **237** based upon monitored CVT operating signals, with controller **240** determining the primary pressure command **241** and secondary pressure command **243** to control operation of the CVT **100** in response to the desired VSR command **205**, the commanded engine torque **223**, the operator torque request **225** and the presently measured actual variator speed ratio **251**.

The CVT control routine **200** described herein uses primary and secondary pressure measurements to determine a relationship between shifting forces and ratio change rate at different conditions. The associated algorithm includes introducing a sinusoidal excitation to the speed or torque ratio of the variator of the CVT in order to calculate the ratio of ratio rate and balance of primary/secondary pulley forces for different conditions. Thus, the CVT control routine **200** determines a variator ratio derivative without relying on noisy differentiation from signal filters and estimators. This is accomplished by employing the frequency component inserted into the excitation signal that includes the desired speed ratio to calculate the variator ratio derivative. In one embodiment the frequency composition is obtained using a discrete FFT and in another a bank of sinusoids at difference frequencies and phases is used. This calculation is then divided by the force balance of the primary/secondary forces at the pulleys of the variator. The division yields a ratio rate coefficient that is characterized for different operation conditions of the variator. The benefits of the procedure are a simpler, more accurate, faster method to relate the ratio of ratio to the balance of primary and secondary forces in the variator of the CVT.

The detailed description and the drawings or figures are supportive and descriptive of the present teachings, but the scope of the present teachings is defined solely by the claims. While some of the best modes and other embodiments for carrying out the present teachings have been described in detail, various alternative designs and embodiments exist for practicing the present teachings defined in the appended claims.

The invention claimed is:

1. A method for controlling a variator of a continuously variable transmission, comprising:

combining, by a controller, a periodically repeating excitation signal and a desired variator speed ratio signal;

determining a variator ratio derivative based upon the desired variator speed ratio signal combined with the excitation signal;

determining a variator control parameter based upon the variator ratio derivative; and

sending the variator control parameter to the controller and controlling the variator in response thereto.

2. The method of claim **1**, wherein combining the periodically repeating excitation signal and the desired variator speed ratio signal comprises combining a sinusoidal excitation signal and the desired variator speed ratio signal.

3. The method of claim **2**, wherein combining the sinusoidal excitation signal comprises introducing a sinusoidal signal having a magnitude that is +/−5% of a maximum value for the desired variator speed ratio signal into the desired variator speed ratio signal.

4. The method of claim **1**, wherein determining a variator ratio derivative based upon the desired variator speed ratio signal combined with the excitation signal comprises taking a derivative with respect to time of the desired variator speed ratio signal combined with the excitation signal.

5. The method of claim **1**, wherein the variator comprises a belt-drive variator including first and second pulleys rotatably coupled via a rotatable device including a first actuator operably connected to a moveable sheave of the first pulley and a second actuator operably connected to a moveable sheave of the second pulley; and

wherein sending the variator control parameter to the controller and controlling the variator in response thereto includes controlling the first and second actuators to control axial positions of the moveable sheaves of the first and second pulleys of the variator.

6. The method of claim **1**, further comprising determining the desired variator speed ratio in response to an operator torque request.

7. The method of claim **6**, further comprising determining the desired variator speed ratio in response to the operator torque request and a torque output from the continuously variable transmission.

8. A method for controlling a variator of a continuously variable transmission, comprising:

determining a command for controlling the variator in response to an operator torque request and a torque output from the continuously variable transmission;

combining, by a controller, a periodically repeating excitation signal and the command for controlling the variator;

determining a variator ratio derivative based upon the command for controlling the variator combined with the excitation signal;

determining a control parameter for the variator based upon the variator ratio derivative; and

sending the control parameter to the controller and controlling the variator in response thereto.

9. The method of claim **8**, wherein combining the periodically repeating excitation signal and the desired variator speed ratio signal comprises combining a sinusoidal excitation signal and the desired variator speed ratio signal.

10. The method of claim **9**, wherein combining the sinusoidal excitation signal comprises introducing a sinusoidal signal having a magnitude that is +/−5% of a maximum value for the desired variator speed ratio signal into the desired variator speed ratio signal.

11. The method of claim **8**, wherein determining a variator ratio derivative based upon the command for controlling the variator combined with the excitation signal comprises taking a derivative with respect to time of the command for controlling the variator combined with the excitation signal.

12. The method of claim **8**, wherein the variator comprises a belt-drive variator including first and second pulleys rotatably coupled via a rotatable device including a first actuator operably connected to a moveable sheave of the first pulley and a second actuator operably connected to a moveable sheave of the second pulley; and

wherein sending the control parameter to the controller and controlling the variator in response thereto comprises controlling the first and second actuators to control axial positions of the moveable sheaves of the first and second pulleys of the variator.

13. A method for controlling a variator of a continuously variable transmission, comprising:

determining a command for controlling the variator in response to an operator torque request and a torque output from the continuously variable transmission;

determining a presently measured actual variator speed ratio;

determining a variator ratio derivative based upon the presently measured actual variator speed ratio;

determining a control parameter for the variator based upon the variator ratio derivative; and sending the variator control parameter to the controller and controlling the variator in response thereto.

14. The method of claim **13**, wherein determining a variator ratio derivative based upon the presently measured actual variator speed ratio comprises taking a derivative with respect to time of the presently measured actual variator speed ratio.

15. The method of claim **13**, further comprising determining the desired variator speed ratio in response to the operator torque request.

16. The method of claim **13**, wherein the variator comprises a belt-drive variator including first and second pulleys rotatably coupled via a rotatable device including a first actuator operably connected to a moveable sheave of the first pulley and a second actuator operably connected to a moveable sheave of the second pulley; and

wherein sending the variator control parameter to the controller and controlling the variator in response thereto comprises controlling the first and second actuators to control axial positions of the moveable sheaves of the first and second pulleys of the variator.

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